The "Bois du Peu" thrust sheets (external French Jura mountains):re-examining the concept of "Fault-Fold"

Grégory Bièvre, Eric Mercier

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Abstract

Significant reconnaissance field work along a road project which crosses the site of the “Bois du Peu" thrust sheets (near Besançon, Eastern France), provides us the opportunity to re-examine the concept of “fault-folding" (in french, “faille-pli”) which was introduced by Glangeaud (1944) to account for the observed tectonics of the Jura mountains and, more specifically, external Jura. From a theoretical point of view, we contend that this concept is incompatible with general principles of balanced cross-sections and has to be rejected. We show that in the “Bois de Peu" area, data fit with a deformation model which associates several modes of folding (fault-propagation fold and fault-bend fold). The decollement level related to these folds is located into Keuper strata, Oxfordian-Argovian levels being used locally as a secondary decollement level.

Keywords: Jura mountains, "fault-fold", décollement tectonics, balanced cross- sections, forward modelling.

1 Introduction

The concept of “faille-pli" (in english “fault-fold"; not to be mistaken with the french term of “pli-faille" which means fault-related fold) was introduced by Glangeaud (1944) to account for the observed tectonics of the Jura mountains and, more specifically, external Jura. The latter consists of kilometer-wide strips (called bundles) which are densely folded and faulted. Relatively tabular sections (called plateaus) are found on both sides of these bundles, with the topographically higher ones lying to the East (Fig. 1).

Glangeaud (1944) proposed that the bundles in these carbonate strata resulted from a process he named “fault-fold" and which is illustrated in figure 2. According to him, a pre-existing normal fault (inherited from a previous distension phase) would have elevated the eastern bloc (relative to the western bloc). Then, during the following compression phase, this eastern bloc covered the topographic surface below on the hanging wall block. Hence, the normal fault turns into a thrust fault and the distorted strata draw a fold structure which spills in the direction of the deformation.

Following a field-trip to the Jura that took place in 1951, this morpho-structural concept became very popular in the French geological community. Glangeaud (1951) illustrated his proposed concept on the cross-sections of the Besançon bundle in the “Bois du Peu" area, 2 km south of the city of Besançon. Later authors such as Caire (1963), Chauve and Perriaux (1974), Chauve (1975) then worked on these sections and further detailed them, thus helping to make the “Bois du Peu" area the reference location for the concept of “fault-folding".

The concept of “fault-folding" remained quite popular for a long time in French geological literature. Several reference books applied the concept to the Jura mountains without discussion (Aubouin 1973, Mattauer 1973, Foucault and Raoult 1980, Dercourt et al. 2006). The concept remained dominant for the Jura mountains until at least the end of the 1980s (Chauve 1987).

During the same period, however, the anglophone (in the sense of non-francophone) community completely ignored the fault-fold concept. Since the end of the 1960s, their approach to the tectonics of the external zones has been based on the concept of balanced cross-sections (Wilson and Stearns 1958, Bally et al 1966, Dahlstrom 1969, to cite only a few pioneering works). Applying this concept, some authors (Laubscher 1961, Mugnier and Vialon 1986, Endignoux and Mugnier 1990, Zoetemeijer and Sassi 1992, Martin and Mercier 1996, Meyer 2000) proposed balanced cross-sections of the Jura bundles without taking into account the concept of “fault-folding". Moreover, Madritsch et al. (2008, 2010) recently proposed that the Besançon zone is affected by thin-skinned tectonics only.

De facto, even if this concept has never been strongly discussed in the literature, it appears inconsistent with the principle of balanced cross-sections and therefore must be abandoned. Since Glangeaud's work (Glangeaud 1951), the "Bois du Peu" area has never been reinterpreted. Geological study and civil engineering works conducted for the Besançon higway by-pass project provide new outcrops and subsurface drillings (corings and tunnels) in the "Bois du Peu" area. This new data provides a good opportunity to re-examine and re-interpret this reference location.

The aim of this paper is first to re-examine the concept of "fault-fold" and to show why it is inconsistent with the concept of balanced cross-sections. The implications of this on Glangeaud's concept will be re-examined. Secondly, new data concerning the "Bois du Peu" area will be presented. This data allows a new detailed geological map to be created. Finally, it will be proposed that a new fault-related fold model is consistent with field observations.

2 Geological context of the study area

The Jura is an arched moutain belt located NW of the Swiss molasse basin (Fig. 1a). The study zone is located in the outer Jura chain and is mainly made of Jurassic carbonate formations (Fig. 3). These sedimentary strata are arranged in relatively tabular plateaus separated by severely folded and faulted narrow elongated bundles (Fig. 1b). This arrangement is the result of the "multi-phased" tectonic history of the area, where two main phases can be distinguished. The first phase was extensional, with an E-W sense and has an Oligocene age. This resulted in a general westward downstepped blocks geometry which corresponds to the present-day look of the massif. The second phase was compressive, directed towards the NW and is Miocene. The deformation related to the compressive phase was principally located at the boundaries between the plateaus, thus generating bundles, characterized by folds and thrust faults (Glangeaud 1951, Caire 1963, Bergerat et al 1990, Guellec et al 1990, Lacombe and Angelier 1993, Martin and Mercier 1996, Homberg et al 1999). Furthermore, the major oligocene-inherited meridian faults induced a leftward strike-slip motion which allowed the panels to slide. According to palaemoagnetic recordings, this translation movement did not induce significant rotation of the structures (Gehring et al 1991).

The Besançon bundle constitues one of the narrow strips. In the study area, this bundle is oriented SW-NE and is about 4 km wide. It is bounded by the Besançon/Thise plateau to the NW and by the topographically higher Montrond plateau to the SE (Fig. 1b). At the outcrop, this bundle is made of two parallel antinclines. To the NW, the Citadel anticline shows a symetric or slightly SE overturned geometry. To the SE, the Mercureaux anticline is strongly dyssimetric and overturned towards the NW (Fig. 1b). It is the Mercureaux anticline, along with its associated Montfaucon fault (Dreyfuss and Kuntz 1968), which have been interpreted as one of the best examples for the “Fault-fold" structure by Glangeaud (1951).

The local geological series consists of alternating soft (clay and marls) and hard levels (limestones, dolomites and sandstones) and is shown in figure 3. The main decollement level is located within the Triassic gypsum-rich strata. Secondary decollement levels may be found within soft Jurassic strata (Fig. 3): Pliensbachian-Aalenian, Oxfordian sensu stricto-Argovian and middle Sequanian. Regional sub-stages denominations (Dreyfuss and Kuntz 1968) have been kept to distinguish between the mechanically variable strata.

The Besançon highway by-pass (Maurin 2001, Bièvre 2007) crosses the Mercureaux anticline in the “Bois du Peu" area. The geological complexity of the site lead to dense prospectings: several kilometers of boreholes, and logging (gamma-ray, microseismics, digital camera) as well as mechanical in situ and laboratoray tests. Furthermore, a reconnaissance gallery has been drilled that crosses the base of one of the bundles. The integration of these new data allow to detail the orientation and dip of faults as well as the lithology of the bedrock underlying the top-soil layer, especially along the Mercureaux anticline axis (Fig. 1b) made of soft clayey and marly formations. The data allows the construction of a detailed geological map of the area as well as an original synthetic cross-section of the bundle which was crossed by the reconnaissance gallery.

3 The concept of “fault-fold" in the light of balanced cross-sections theory

The theory of balanced cross-sections is based on the assumption that thanks to the law of conservation of matter, the amount of material remains constant during tectonic deformations. In faults and folds belts, it is often possible to work on cross-sections (see complete discussion in Marshak and Woodward (1988) for example) and, in this way, to transform the law of conservation of matter into a law of conservation of surfaces (i.e. during deformation, the surface of each bed remains constant). To verify this conservation, it is necessary to set boundaries on the system studied and, consequently, to discuss the conditions of these boundaries.

Figure 4 shows that surface conservation requires that, during the growth of a “fault-fold", the boundaries of the system undergo differential simple shear. This diagram shows that only the upper layers of the upper block suffer simple shear during horizontal shortening. More specifically, only the beds which are in elevation over the top of lower block after the first deformation (normal fault) suffer simple shear. This is problematic because, obviously, the boundary conditions are controled by rear area deformation conditions and not by internal parameters (normal fault offset) as the figure might falsely imply.

Furthermore, Figure 5 shows that the deformations are amortized into the structure and are not transfered forward from one block to another. Accordingly, this model fails to explain the succession of several “fault-fold" strutures on a unique cross-section as is the case in the Jura (Chauve 1987).

A high proportion of authors who recently worked on the Jura (see above), appear to have abandoned the concept of “fault-fold". None of these authors have justified this abandonment however, and the concept of fault-folding therefore goes unmentioned. We have shown that the concept of “fault-folding" is incompatible with the theory of balanced cross-sections, this incoherence being the reason for the abandonement. The “Bois de Peu “area, the reference location for the concept of “fault-folding", therefore has to be explained otherwise. The following sections show that it is possible to reinterpret this structure using the concepts of “fold and fault-belts" tectonics.

4 Results

4.1 Geological field data

Surveys conducted for the highway by-pass study provided a large amount of geological data (Maurin 2001, Bièvre 2007). Combined with detailed field observations, these data allow us to produce a new geological map based on a previously established one (Dreyfuss and Kuntz 1968). There is no fundamental change between the two maps, but the one that is proposed here is much more detailed (Fig. 6) due to new available data. In combination with these field observations, a reconnaisance gallery was drilled through the base of one of the “Bois du Peu" thrust sheets and an interpretative cross-section was built (Fig. 7; modified from CETU 1999).

The proposed cross-section for this work is located one km SW of the reference location. The geological map reveals that fault F2 dips towards the SE (as it has been revealed by corings and gamma-ray logging; Maurin

2001). Fault breccia was found in corings conducted along the road project to define the dip of F3 (Bièvre 2007). Along with the gamma-ray logging in surrounding drillings, this reveals that the F3 fault (Montfaucon fault of Dreyfuss and Kuntz 1968) slighlty dips towards the SE (Fig. 6). These two faults were previsously considered to be subvertical (Fig. 8a; Glangeaud 1951, Caire 1963, Chauve and Perriaux 1974, Chauve 1975). Moreover, the Mercureaux anticline axis is located a few hundred metres SE of F3 (Fig. 6; Bièvre, 2007). These two initial observations are inconsistent with the “fault-fold” interpretation of the area “.

A vast outcrop composed of Triassic strata is present in contact with F3 along the road project, 200 m SE of the tunnel (location on Fig. 6). This Triassic outcrop is bordered by Pliensbachian strata (Belemnites as well as Ammonite Amaltheus margaritatus were found in corings). Associated with the presence of fault breccia, cartography and orientations of dips, these elements allow this Triassic outcrop to be considered as a tectonic flake forced against the Montfaucon fault (F3). The presence of such a flake constitutes an important argument to interpret F3 like a thrust fault seated within Triassic strata (Fig. 8b).

The hinge and inverted limb, situated NW of the Mercureaux anticline overthrust the very competent Jurassic beds. In first approximation, despite some irregularities (Fig. 7 and Fig. 8), this thrust is parallel to the autochton stratification. Previous authors had considered implicitly (compare Fig. 3 and Fig. 8a) or explicitly that the thrust surface was the Pontian topographic surface (surface of “Montrond"; Dreyfuss and Glangeaud 1950). This hypothesis is discussed further in section XXX.

Thrust F1 is not the only one to be locally parallel with the stratification. For example, thrust F2 is, from NW to SE, successively sub-parallel, oblique and again sub-parallel with the stratification(Fig. 8b). These particular relations refer to the ramp geometry. This observation, along with previous works on other bundles in the Jura (Endignoux and Mugnier 1990, Zoetemeijer and Sassi 1992, Martin and Mercier 1996, Meyer 2000), lead us to propose a kinematic scheme characterized by the development of folds-related ramps for the “Bois de Peu" area.

4.2 Kinematic modelling

Cross-section balancing has become a standard method for testing viability and admissibility of hypothetical deep geometry. Many theoretical and applied works have focused on this method in thrust and fold belts. Several approaches have been developed but, according to most of the authors, in the Jura, the “forward" method is the most appropriate (Endignoux and Mugnier 1990, Zoetemeijer and Sassi 1992, Martin and Mercier 1996). Martin and Mercier (1996) proposed a comprehensive discussion on the application of this method to a bundle of the Jura. To summarise, this method provides a viable and admissible kinematic pathway between an initial state (undeformed) and a final state (deformed). The need to respect the law of conservation of matter (1) between initial stage and final stage, and (2) between each kinematic step, strongly limits the number of possible solutions.

In practice, a trial and error process was used to build an image of the finite deformation which is consistent with field data. With this kind of problem solving process, there is a risk of neglecting alternative solutions. Hence, many tests were carried out to assess the influence of changes in calibration parameters.

In this study, we chose to work on an “average" cross-section. This section can be considered as representative of the whole area, and allows the elimination of local variations that can not be taken into account by modelling. The numerical solution is shown in figure 9.

Steps a, b and c: a “fault-propagation fold" (in the sense of Suppe 1985) gradually grows over a ramp deeply-seated in a decollement level located at the top of the Triassic strata. It has long been known (e.g. Glangeaud 1951, Caire 1963) that the Jura bundles are the result of the superposition of an Oligocene tectonic distension and a Miocene tectonic compression. Previous modelling works (Martin and Mercier 1996) showed that in the bundle, ramp initiation occurs systematically at the intersection between a decollement level and inherited normal faults. Surprisingly, there are no arguments in these works to link the initiation of the ramp with a normal fault.

Step d: the fault-propagation fold suffers a standard late evolution: transport on the flat (Mercier 1992; Mercier et al 1997). Usually, such evolution occurs when the ramp can no longer propagate upwards (when the ramp crosses very competent beds, for example), and seeps into an interbed level. It does not seem to be the case here, the very competent Jurassic series is already crossed and the Cretaceous series, thin and weakly competent, can not stop the propagation of the ramp. The simplest is to assume that the allochton slept upon the paleo-surface topography ("Montrond" surface; Dreyfuss and Glangeaud 1950).

Step e: The transport on the flat becomes increasingly difficult (friction increasing, blocking on local microtopography) and the mechanical conditions in autochton change because of the tectonic overload. A new thrust plane is established.

The movement over this thrust creates a duplex which is transported under the fold. Modeling suggests that this duplex is deep-seated in a secondary detachment level in the Oxfordian-Argovian strata. This hypothesis is fully consistent with mechanical properties of these levels (Fig. 3) and field data (Fig. 6).

Step f: After a significant displacement, this new thrust is blocked in turn. Out-of-sequence thrusts occur from the existing ramps and through weakened areas of the structure (Mercier and Mansy 1995). The northern out-of-sequence fault corresponds to the “forelimb breakthrough" of fault-propagation folds (Mercier 1992). It isolates, between F1 and F3, a small thrust sheet with reverse polarity. We suggest that this thrust sheet is torn into several elements that are more or less carried forward in reponse to the movement of the allochton.

Finally, synchronically or not, growth of the Citadel anticline, located just NW of the section studied, affects the whole structure which is partly integrated into its SE limb. The final bending is not really taken into account by our modeling. The surface topography drawn in figure 9f is distorted from reality, but this adjustment imprecision does not affect the principle and the conclusions of our model. In fact, it only introduces an uncertainty on the geometric modeling of the out-of-sequence faults F4 and F4’.

The total shortening, of about 50 % (4 km), is significantly higher than what was calculated on the sections located further north accross the same bundle (Martin and Mercier 1996). This difference suggests small rotations of the plateaus during deformation.

5 Discussion and conclusions

Major geological reconnaissance for the Besançon by-pass took place in the reference location for the concept of “fault-folding” (“Bois du Peu” area; Glangeaud 1951). It provides firstly an opportunity to discuss this concept of “fault-folding”, and to show its incompatibility with the theory of balanced cross-sections. Secondly, it allows us to propose a new structural evolution for this area (Fig. 8b and Fig. 9).

We show that available field data are consistent with a typical scenario of folds and thrust belt evolution, particularly characterized by the growth and evolution of fault-related folds deeply seated within Triassic strata. This is very similar to scenarios already proposed for other Jura bundles (e.g. Guellec et al 1990, Martin and

Mercier 1996, Meyer 2000). In particular, we note the combination of various folding modes (fault-related folds with late evolution, duplex, etc.) in the same sector. This work, among many others, confirms the utility of the “forward" method in the study of the Jura tectonics. However, without syntectonic sedimentary markers, the sequence of deformation proposed remains, in the study case as elsewhere, poorly constrained. In the study area, the shortening is about 50% which is higher than what is known in other bundles. Finally, we note the importance of earlier morphological evolution in the development of some thrust faults wich slip onto a paleo-erosion surface.

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Figure 1: Location of the study area and strutural map of the Besançon area. a) Strutural map of the Jura mountains around Besançon showing the organization in plateaus and bundles (simplified from Madritsch et al. 2008). b) Detailed structural map of the study area (location on Fig. 1a) showing the main faults and folded structures (adapted from Dreyfuss and Kuntz 1968). CA: Citadelle anticline; MA: Mercureaux anticline; MF: Mercureaux fault; TF: Trochatey fault.

Figure 2: The kinematics of a “fault-fold" according to Glangeaud (1944).

Figure 3: Synthetic lithologic log of the Besançon area showing the alternation of clays/marls soft levels with hard limestone layers. The main decollement level is located within the upper Keuper layers; Pliensbachian-Aalenian, Oxfordian-Argovian and middle Sequanian layers may serve as secondary décollement levels. Oxf. s.s.: Oxfordian sensu stricto. Arg.: Argovian. Raur.: Rauracian. Seq.: Sequanian.

Figure 4: An attempt to integrate the concept of “fault-fold" in a balanced cross-section. To balance the structure (same as step b on Fig. 2), layers have to be subject to a simple shear whose characteristics depend on the inherited fault net slip.

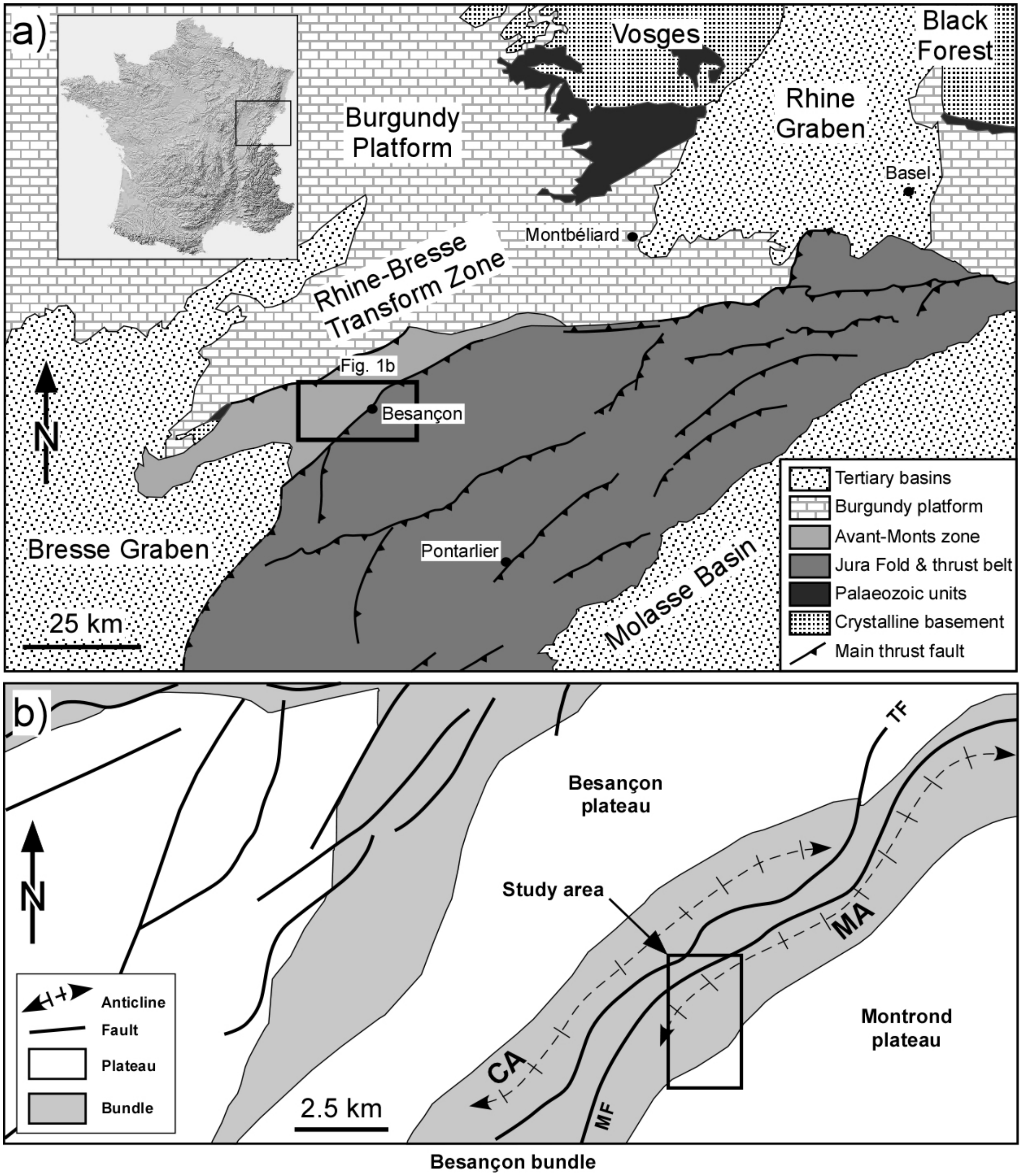
Figure 5: Non-balanced cross-section showing that a “fault-fold" is unable to transmit forward the deformation necessary to the growth of a second “fault-fold". Examination of this diagram shows that the upper part of the central flat can not undergo at the same 1) a moderate shear resulting from the deformation coming from the back and 2) a significant shear necessary to generate the forward (left) structure.

Figure 6: Geological map of the study area, location of the road works (bold dashed black line) and of the “Bois du Peu" tunnel (black rectangle). Coordinates are metric according to the French Lambert II system. BdP.T.: Bois de Peu tunnel and cross-section of figure 7. faults are named after Dreyfuss and Kuntz (1968). F1 to F5: faults. Map adapted from Dreyfuss and Kuntz (1968) and Bièvre (2007).

Figure 7: Geological cross-section of the “Bois du Peu’ tunnel. Faults are labelled in the same manner as in Fig. 6. Modified from CETU (1999).

Figure 8: Cross-sections of the “Bois du Peu" area. a: Interpretation in terms of a “fault-fold" (according to Glangeaud 1951, Chauve and Perriaux 1974). Faults are labelled in the same manner as in Fig. 6. The fault associated to the “fault-fold" structure corresponds to F1 and to the lower part of F3. The uppert part of F3 would be the result of a late reactivation Chauve (1975). b: Proposed interpretation according to new data and balanced cross-sections. Position of Figure 7 is indicated. See text for details.

Figure 9: Kinematic evolution of the Besançon bundle in the study area based on balanced cross-sections and using a forward modelling approach. Faults are labelled in the same manner as in Fig. 6. M.A.: Mercureaux anticline. BdP.T.S.: “Bois du Peu" thrust sheets. Step a to f: see text for details.


a)
Vosges
Black Forest
Rhine Graben
Burgundy Platform
Basel
Montbéliard
Rhine-Bresse Transform Zone
Fig. 1b
Besançon
Bresse Graben
Pontarlier
Molasse Basin
25 km
N
Tertiary basins
Burgundy platform
Avant-Monts zone
Jura Fold & thrust belt
Palaeozoic units
Crystalline basement
Main thrust fault
b)
Besançon plateau
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Besançon bundle

Figure 1

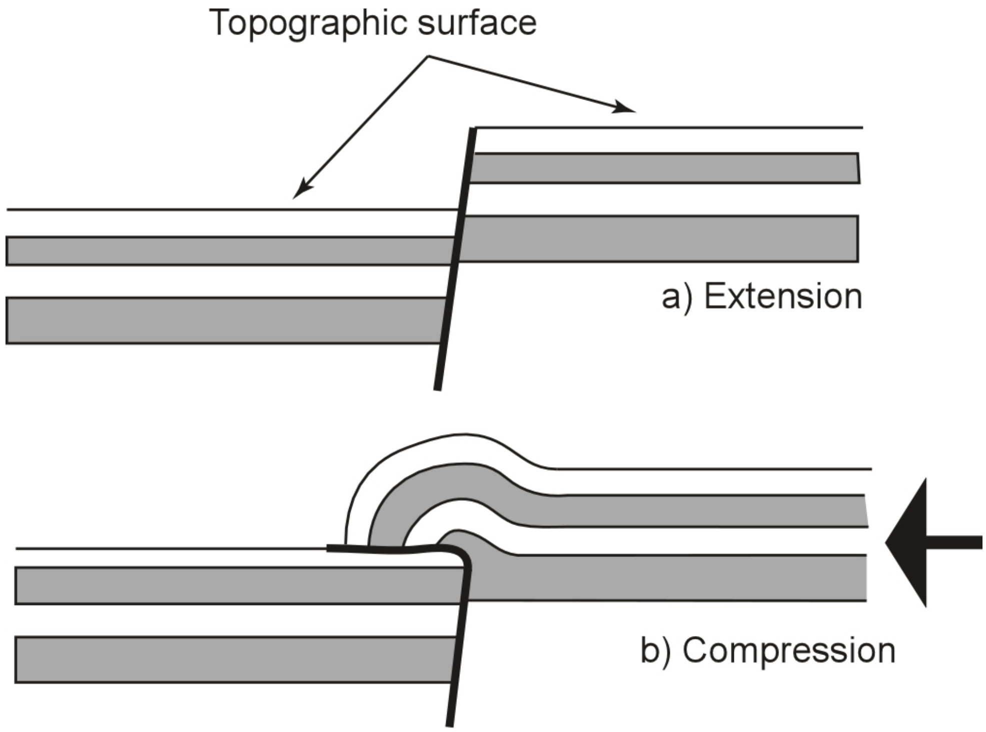
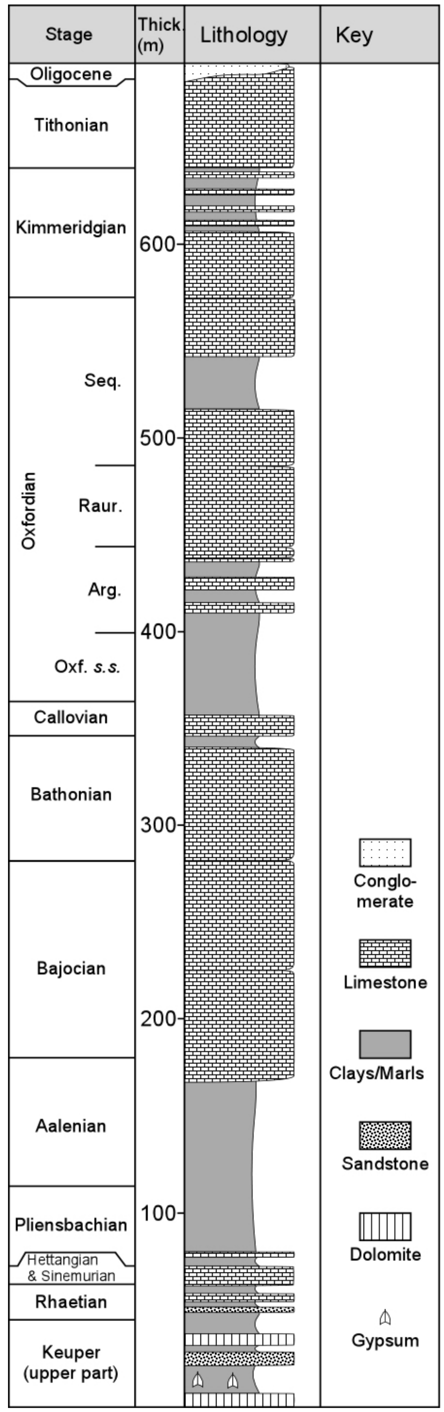


Figure 2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Raur.
Arg.
Oxf. s.s.
Callovian
Bathonian
Bajocian
Aalenian
Pliensbachian
Hettangian & Sinemurian
Rhaetian
Keuper (upper part)
600
500
400
300
200
100
Conglo-merate
Limestone
Clays/Marls
Sandstone
Dolomite
Gypsum

Figure 3

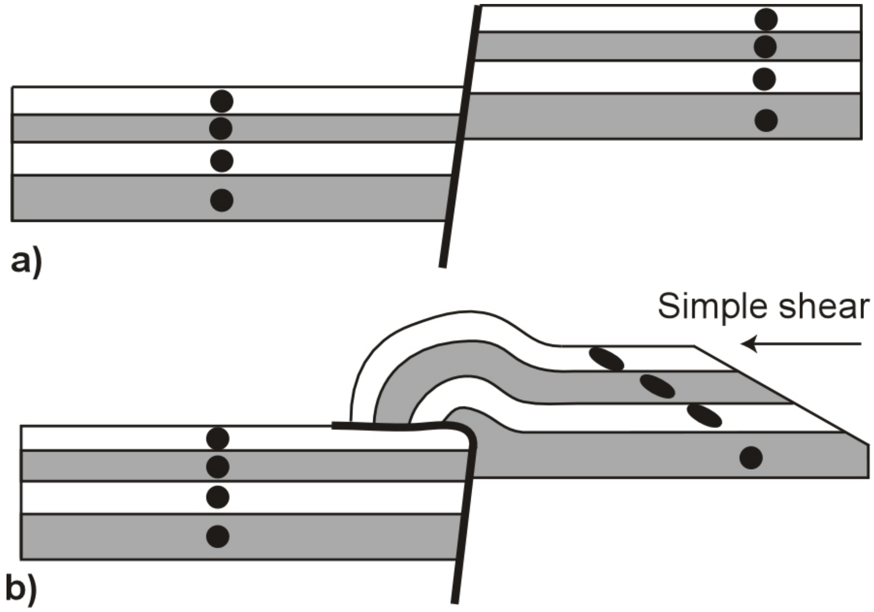

Figure 4

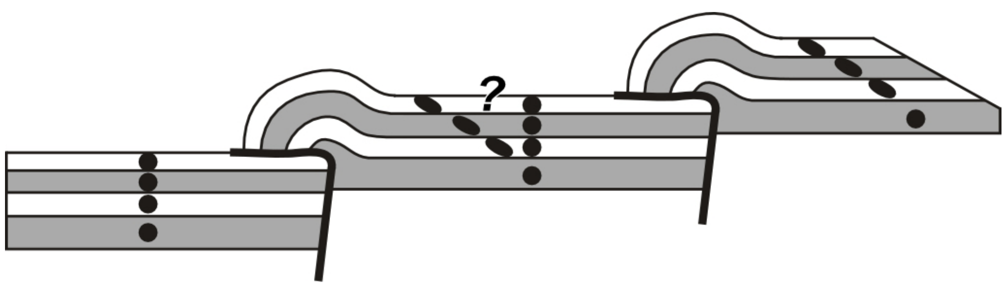

Figure 5

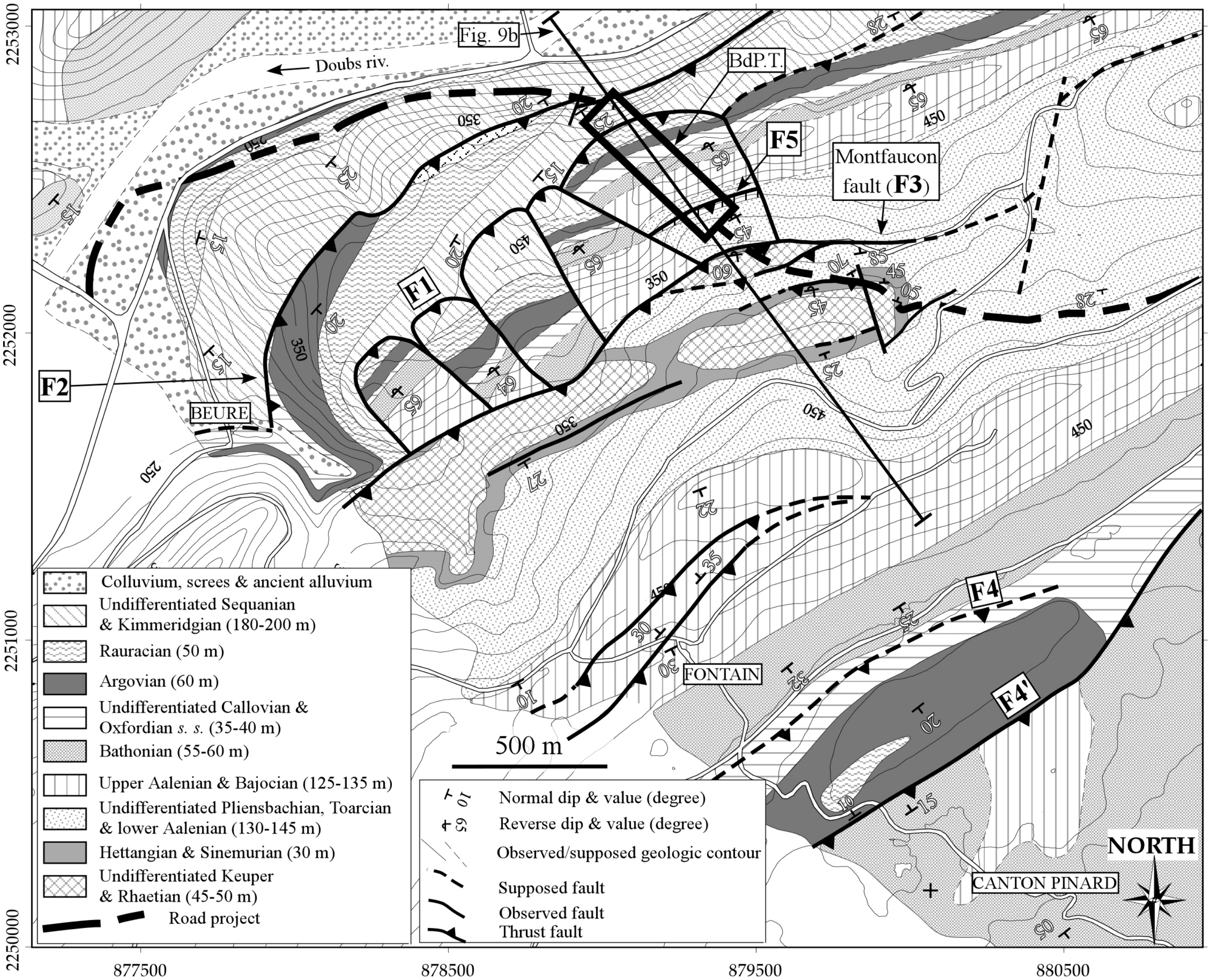
Fig. 9b
Doubs riv.
BdP.T.
F5
Montfaucon
fault (F3)
F1
F2
BEURE
FONTAIN
F4
F4'
CANTON PINARD
NORTH
500 m
2253000
2252000
2251000
2250000
877500
878500
879500
880500
Colluvium, screes & ancient alluvium
Undifferentiated Sequanian
& Kimmeridgian (180-200 m)
Rauracian (50 m)
Argovian (60 m)
Undifferentiated Callovian &
Oxfordian s. s. (35-40 m)
Bathonian (55-60 m)
Upper Aalenian & Bajocian (125-135 m)
Undifferentiated Pliensbachian, Toarcian
& lower Aalenian (130-145 m)
Hettangian & Sinemurian (30 m)
Undifferentiated Keuper
& Rhaetian (45-50 m)
Road project
Normal dip & value (degree)
Reverse dip & value (degree)
Observed/supposed geologic contour
Supposed fault
Observed fault
Thrust fault

Figure 6

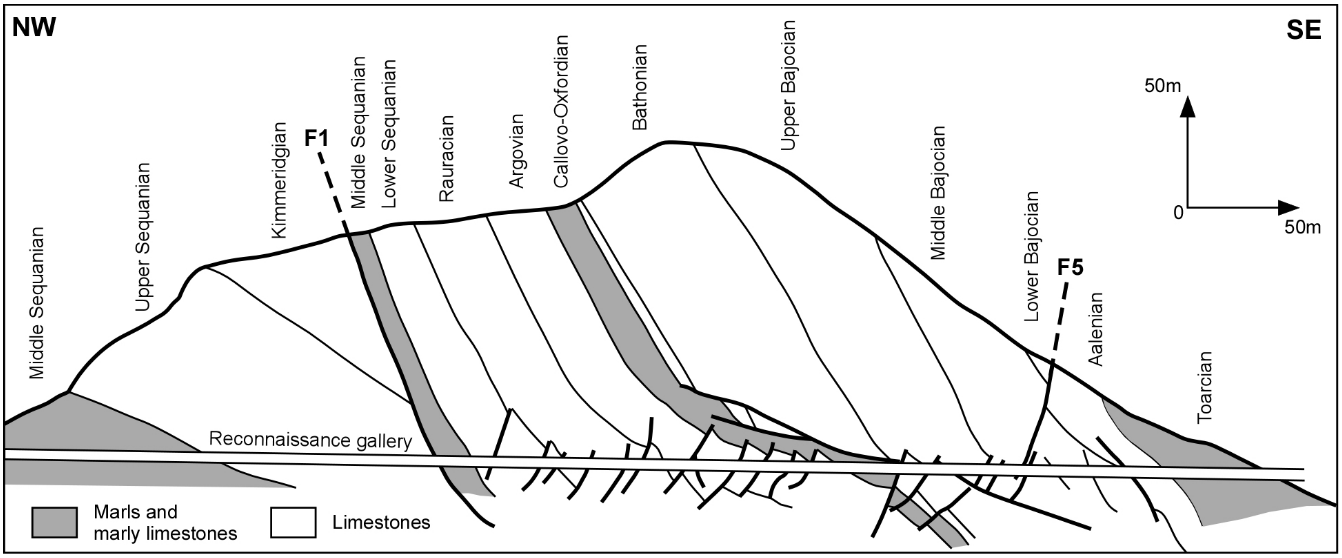

Figure 7

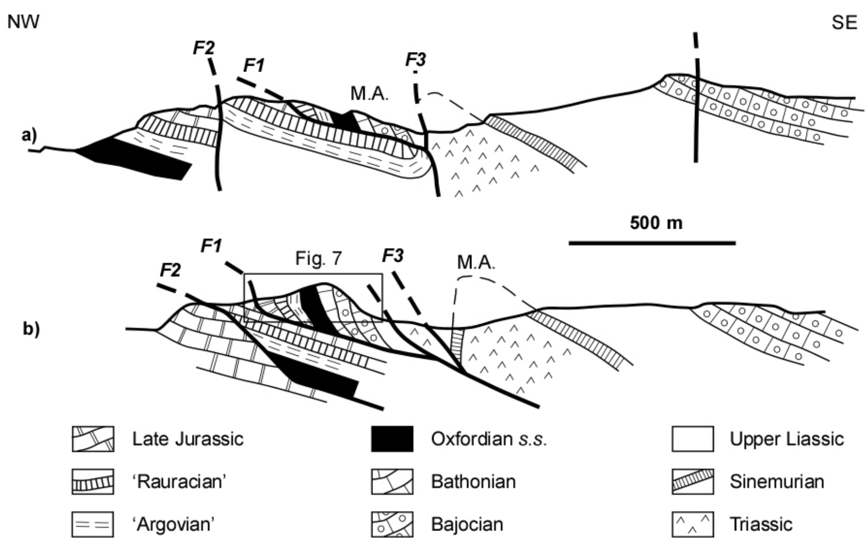

Figure 8

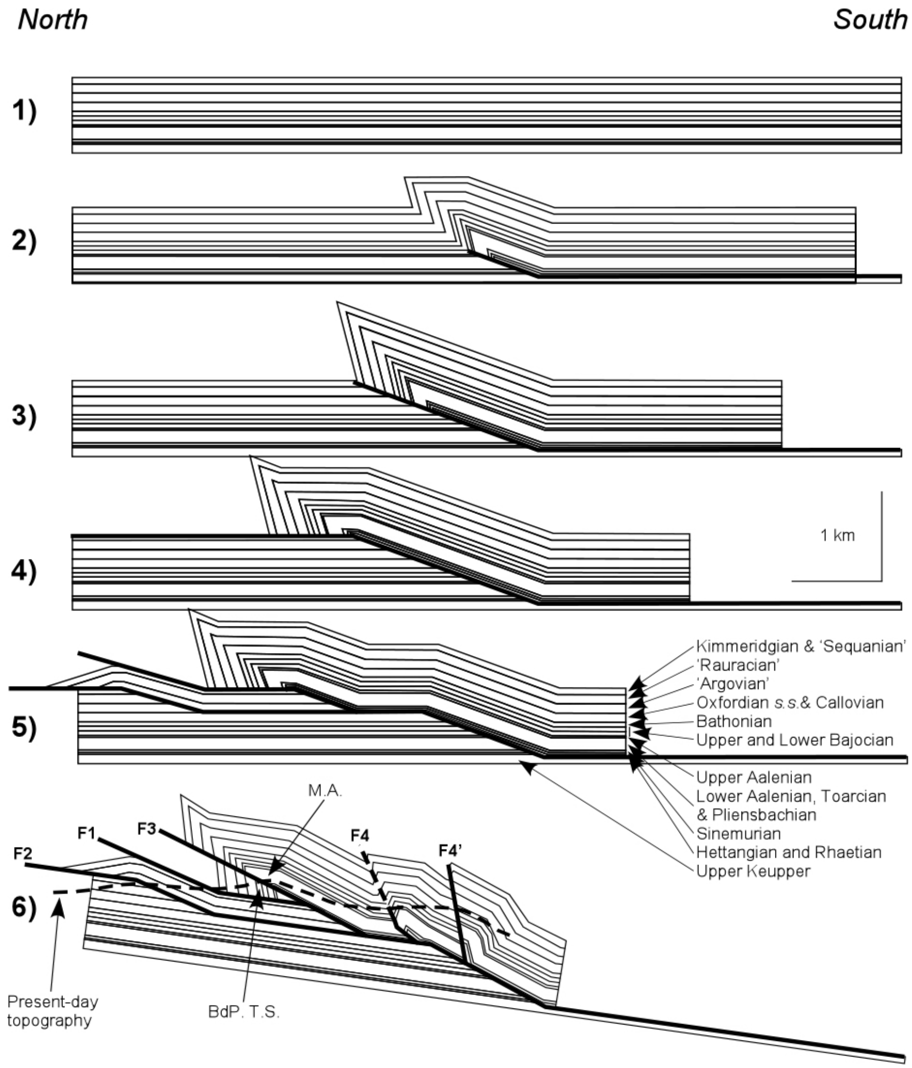
North
South
1)
2)
3)
4)
1 km
5)
Kimmeridgian & 'Sequanian'
'Rauracian'
'Argovian'
Oxfordian s.s.& Callovian
Bathonian
Upper and Lower Bajocian
Upper Aalenian
Lower Aalenian, Toarcian
& Pliensbachian
Sinemurian
Hettangian and Rhaetian
Upper Keupper
6)
M.A.
F1
F2
F3
F4
F4'
Present-day
topography
BdP. T.S.

Figure 9